COSMIC STAR-FORMATION HISTORY, AS TRACED BY RADIO SOURCE EVOLUTION.

J.S. DUNLOP

Institute for Astronomy, Department of Physics & Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK.

Abstract.

I briefly review our current knowledge of the cosmological evolution of radio sources, and show that the redshift distributions of new complete samples of radio sources confirm the existence of the high-redshift decline in comoving number density (or 'cutoff') beyond $z \simeq 2.5$ first deduced by Dunlop & Peacock (1990). Taken at face value these new data favour a luminosity dependent 'cutoff', in which the decline is least drastic for the most luminous radio sources. I demonstrate, however, that regardless of the precise form of radio source evolution, the evolution of radio luminosity density is well determined, and appears uncannily similar to the evolution of ultra-violet luminosity density from star-forming galaxies in the universe (*e.g.* Madau 1997). I convert radio luminosity density into an estimate of black hole fueling rate per Mpc^3, and conclude that radio source evolution is a good tracer of the star-formation history of the Universe; at any epoch, for every 10^7 $M_\odot$ of material converted into stars, approximately 1 $M_\odot$ appears to be consumed by radio-loud active galactic nuclei. If this is indeed true at all epochs, then this would imply that star-formation activity in the Universe peaked at $z \simeq 2 - 2.5$, and that the values of star-formation rate density currently derived from Lyman-limit galaxies at $z \simeq 2.8$ and $z \simeq 4$ are under-estimates by a factor $\simeq 4$. Finally I briefly speculate as to why radio source evolution might trace global star-formation activity as manifested primarily in the disc/spiral population, whereas the hosts of the radio sources themselves generally appear to be well-evolved elliptical galaxies.

1. Introduction

The past year has seen the first meaningful attempts to determine the global star-formation history of the Universe, using the combined leverage provided by deep redshift surveys (*e.g.* the Canada France Redshift Survey (CFRS); Lilly *et al.* 1995) reaching $z \simeq 1$, and the detection/non-detection of Lyman limit galaxies at higher redshifts (in, for example, the Hubble Deep Field; Madau *et al.* 1996). The results (*e.g.* Madau 1997) indicate that star-formation rate (and metal production)

is $\simeq 10$ times greater at $z \simeq 1$ than in the local Universe, peaks somewhere around $z \simeq 1 - 2$, and declines to values comparable with the present day at $z \simeq 4$. The impact of dust obscuration on this result has yet to be fully assessed (Pettini, priv. comm.), as has the effect of combining samples selected in rather different ways. However, amid the excitement caused by this revolution in optical cosmology, it seems to have been forgotten that there already exists a class of source the evolution of which has been well studied out to $z \simeq 4$, is derived from well-defined complete samples, and is immune from the effects of dust.

Since the benefits of studying cosmological evolution at radio wavelengths are so clear, an outsider might reasonably ask why so much effort has recently been directed at determining the cosmological evolution of ultraviolet light in our Universe. The answer, of course, is a general (and not unreasonable) disbelief that the evolution of these rare and bizarre fireworks – powerful radio galaxies – can tell us much (or indeed anything) about the evolution of the 'normal' galaxies of stars. However, in recent years it has become clear that the level and form of evolution displayed by powerful radio sources is not unique to either this particular class of active galaxy or to the radio waveband. As has been discussed elsewhere (*e.g.* Dunlop 1994) at least out to $z \simeq 2$ very similar evolution is found at optical wavelengths for optically-selected QSOs (Hewett *et al.* 1993) and at X-ray wavelengths for X-ray selected quasars (Boyle *et al.* 1993). More intriguing still, however, is the suggestion that the starburst galaxy population discovered by IRAS also displays similar evolution (Rowan-Robinson *et al.* 1993), at least at low z.

This last comparison suggests that the form of evolution displayed by radio sources, as well as being applicable to AGN in general, might be of even wider relevance. In this brief article I have therefore explored the possibility that this evolution is truly universal, by comparing the evolving radio luminosity density from powerful radio sources with recent estimates of the star-formation history of the Universe. First, however, I reassess our current knowledge of the high-redshift evolution of radio sources by comparing the predictions of the alternative high-redshift 'cutoff' models of Dunlop & Peacock (1990) with the actual redshift distributions of two new complete samples; a 'bright' (2 Jy) sample with complete redshift coverage, and the first 'faint' sample (1 mJy) with spectroscopic redshifts or 'reliable' estimates for all sources.

2. The Cosmological Evolution of Radio Sources

The advantages of completeness and immunity to dust offered by radio selection can only be realised with reliable redshift information, which is hardest to achieve at high redshift.

2.1. 'LOW'-REDSHIFT EVOLUTION

Out to redshifts $z \simeq 2$ the evolution of powerful ($P_{2.7GHz} > 10^{26}\mathrm{WHz^{-1}sr^{-1}}$) radio sources is reasonably well-constrained, and in 1990 John Peacock and I showed that, given the existing complete-sample database, the evolution of both the flat-spectrum ($\alpha < 0.5$ where $f_\nu \propto \nu^{-\alpha}$) and steep-spectrum ($\alpha > 0.5$) radio-

source populations is at least consistent with pure luminosity evolution (PLE) with $P(z) \propto (1 + z)^3$ (Dunlop & Peacock 1990).

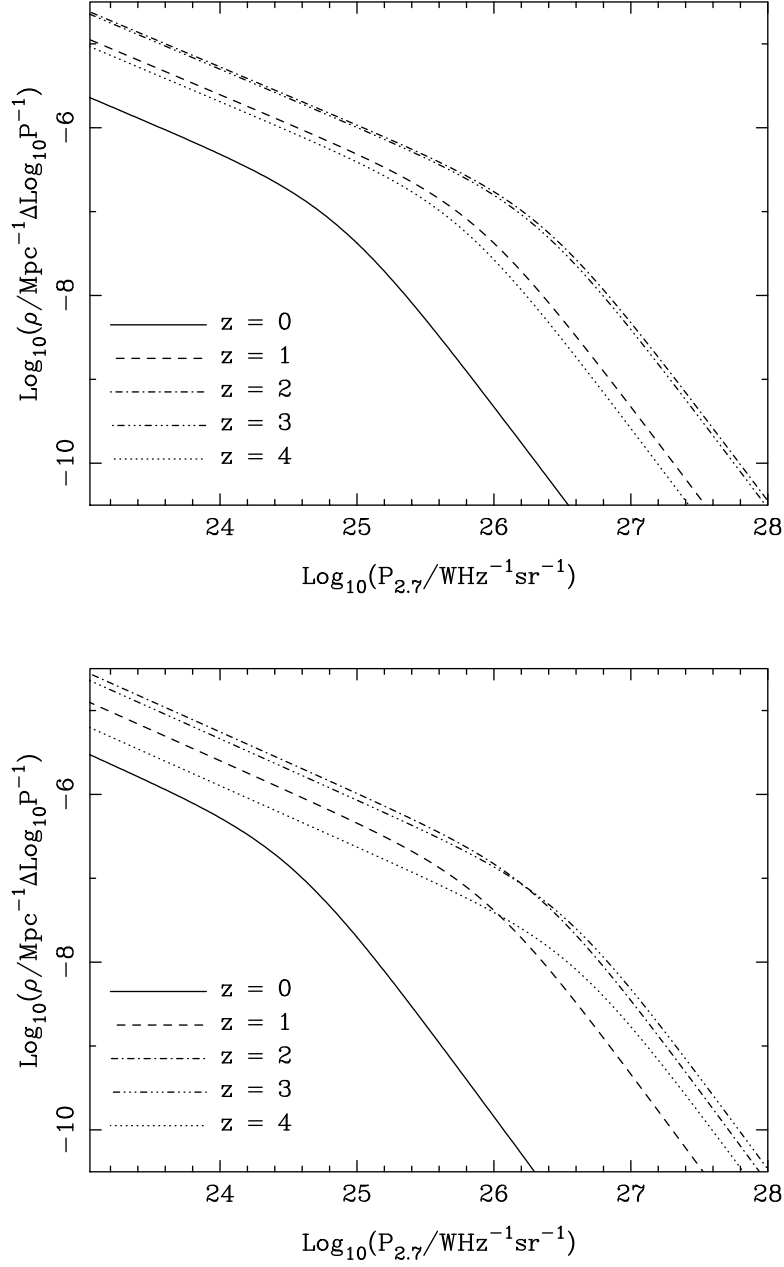## 2.2. HIGH-REDSHIFT EVOLUTION: THE REDSHIFT CUTOFF REVISITED

The key component of the complete-sample database used by Dunlop & Peacock (1990) to constrain the high-redshift evolution of the radio luminosity function (RLF) was the Parkes Selected Regions (PSR), a sample of 178 sources with $S_{2.7GHz} > 100$ mJy over an area of 0.075 sr. Much of the evidence for a high-redshift decline in the steep-spectrum population then depended on K-band photometry to estimate the redshifts of the faintest galaxies in this sample. The reliability of this method has since been called into question (Eales *et al.* 1993) although interestingly a renewed spectroscopic campaign on the PSR is currently revealing that virtually all the galaxies have true redshifts which are *smaller* than their $K - z$ estimates. The revised redshift distribution for the PSR, and its implications for the high-redshift evolution of the RLF will be presented elsewhere. However, a complete redshift distribution has now been obtained for a smaller and brighter complete sub-sample of 65 radio galaxies from the 6C/B2 survey (Eales & Rawlings 1996). Below I compare this redshift distribution with the predictions of the redshift cutoff models of Dunlop & Peacock (1990), and then consider the redshift distribution that John Peacock and I have recently derived for a much deeper sample from the Leiden Berkeley Deep Survey (LBDS), a sample of sufficient depth to resolve the issue of the redshift cutoff beyond doubt.

2.2.1. *Alternative models for the redshift cutoff*
Although Dunlop & Peacock (1990) concluded that the evidence for a high-redshift cutoff in the steep-spectrum luminosity function was strong, uncertainties in redshift estimation, combined with lack of coverage of the luminosity baseline, meant that we were unable to distinguish between universal negative pure luminosity evolution at $z > 2.5$ (the PLE model) and an alternative model involving continuing positive luminosity evolution combined with negative density evolution at high z (the LDE model). These two alternative models are illustrated in Fig. 1, the principle difference between them being that in the LDE model the strength of the decline in comoving number density is a function of radio power.

2.2.2. *Comparison with the complete 6C sub-sample*
The complete 6C/B2 sub-sample consists of 65 sources detected at 151 MHz with 2.2Jy $< S_{151MHz} < 4$Jy in 0.1 sr of sky. Eales, Rawlings and collaborators have recently completed the measurement of spectroscopic redshifts for all the sources in this sample; 11 galaxies lie at $z > 2$ (Eales & Rawlings 1996) and two of these lie at $z > 3$ (6C 1232+39; $z = 3.221$ and B2 0902+34; $z = 3.395$). The cumulative redshift distribution for this sample for $z > 2$ is shown in Fig. 2a, where it is compared with the distributions predicted by the PLE and LDE redshift cutoff models shown in Fig. 1, and also with the prediction of a 'no-cutoff' model in which the form and normalization of the RLF is frozen for $z > 2$. The predicted number counts at 151 MHz have been produced from the models (which are defined at 2.7 GHz) by

Figure 1. Two simple alternative models produced by Dunlop & Peacock (1990) to describe the high-redshift decline in the comoving number density of steep-spectrum radio sources. The upper panel shows the PLE model in which the redshift cutoff is parameterized in terms of universal negative luminosity evolution at high z. The lower panel shows the LDE model in which continuing positive luminosity evolution is overcome by negative density evolution at all powers for $z > 3$. In the latter model the apparent severity of the redshift cutoff becomes a function of radio luminosity, with the most luminous sources suffering a less dramatic, but still significant decline in comoving number density.

using the average spectral index displayed between 151 MHz and 2.7 GHz by the 11 $z > 2$ sources in the sample ($\langle \alpha_{151MHz}^{2.7GHz} \rangle = 0.87$) to convert the 151 MHz flux-density boundaries to their equivalent values at 2.7 GHz. (0.164mJy $< S_{2.7GHz} <$ 0.298mJy). It is clear that the redshift distribution of this sample strongly supports the existence of the redshift cutoff, but that the form of this cutoff seems better described by the LDE model than the PLE model. I note in passing that the recent discovery of 6C 0140+326 at $z = 4.41$ in a deeper 6C ($S_{151MHz} = 1 \rightarrow 2$ Jy) 0.1 sr sample (Rawlings *et al.* 1996) is also perfectly consistent with the LDE model of the high-redshift cutoff (see Dunlop 1996)

### 2.2.3. *Comparison with the new LBDS sample*

The 6C/B2 sub-sample considered above is of interest because of its complete redshift information rather than because it can really confirm or refute the existence of the redshift cutoff. Indeed it is a factor $\simeq 2$ *less* deep than the PSR, and thus at $z > 3$ can only be used to estimate the comoving space density of objects brighter than $P_{2.7GHz} \simeq 10^{27}$WHz^{-1}sr^{-1} (which are intrinsically very rare). To unambiguously confirm or refute the existence of the redshift cutoff really requires the study of a sample which is $\simeq 100$ times fainter, and is thus capable of sampling the radio luminosity function down to $P_{2.7} \simeq 10^{24}$WHz^{-1}sr^{-1} out to $z \simeq 4$ (*i.e.* below the break luminosity at all redshifts – see Fig. 1).

Accordingly, over the last few years we have been attempting to determine the redshift distribution of a statistically complete sample of 77 galaxies with $S_{1.4GHz} > 1$ mJy selected from the LBDS (Windhorst *et al.* 1984a, 1984b, Kron *et al.* 1985). We now possess g, r, i, J, H, K photometry for the galaxies in this sample enabling us to estimate redshifts both from spectral fitting and from a modified version of the $K - z$ diagram (Dunlop *et al.* 1995). Optical spectroscopy of a subset of sources with the Keck telescope shows this dual-pronged approach to redshift estimation to be reliable, certainly out to $z \simeq 2.5$, principally because the starlight from these more moderate-luminosity radio galaxies is less contaminated by strong emission lines or scattered AGN light than in the more extreme high-z objects found in brighter radio samples (Dunlop *et al.* 1996).

The resulting redshift distribution of this 1 mJy sample is compared with that predicted by the PLE-cutoff, LDE-cutoff and no-cutoff models in Fig. 2b, where the predicted redshift distributions have been produced assuming $\alpha_{1.4GHz}^{2.7GHz} \simeq 0.8$. Comparison of the number count predictions in this figure with those in Fig. 2a makes clear the enormous power of this much deeper sample, despite the need to resort to redshift estimation. In fact, to remove the cutoff, 10 of the 77 sources in this sample need to lie at $z > 4$, whereas our best estimate of the redshift distribution follows almost exactly the predictions of the cutoff models.

3. Universal Evolution

The combination of the LBDS and 6C samples spans sufficient baseline in radio power to allow a first attempt at differentiating between the PLE and LDE models, and it is clear that Fig. 2 favours a luminosity-dependent cutoff which is least drastic for the most luminous sources. Large redshift surveys of bright radio
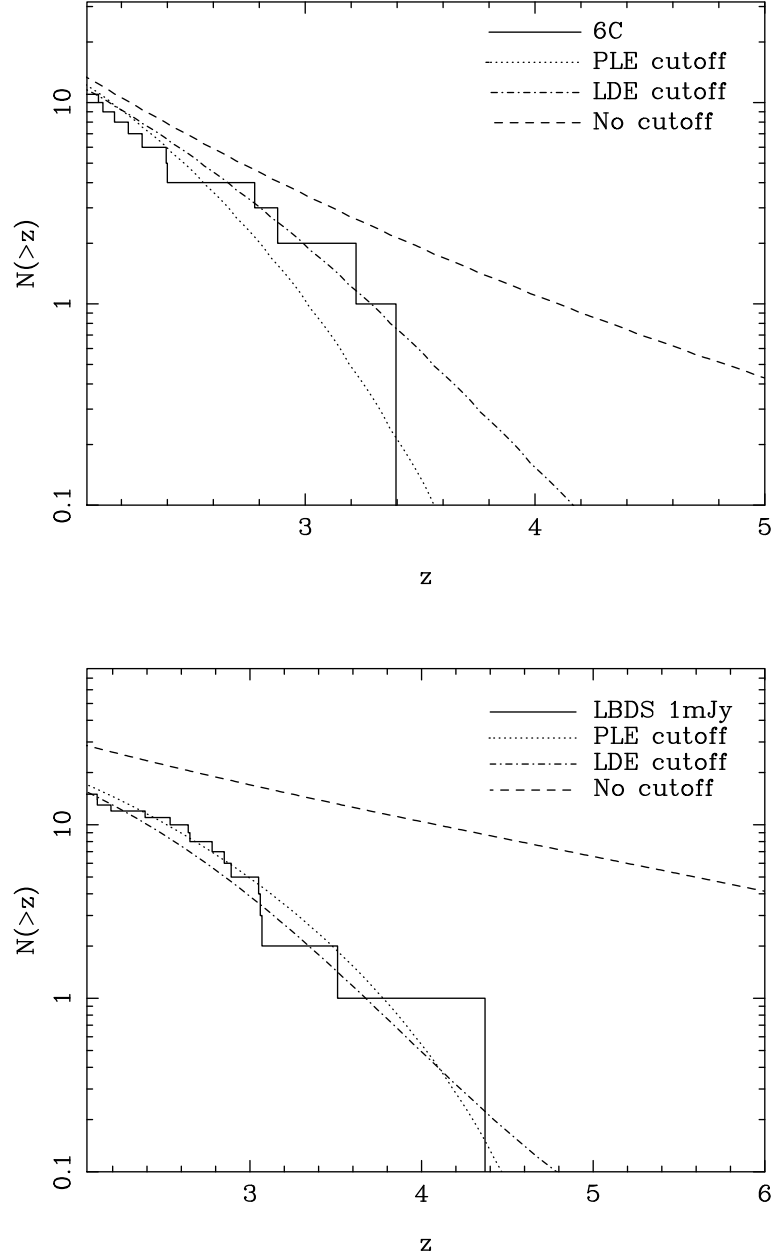
Figure 2.   **Upper Panel:** The observed high-redshift cumulative redshift distribution for the complete 6C/B2 sub-sample, compared with the predictions of the PLE and LDE cutoff models presented in Fig. 1, and with the predicted redshift distribution for a model in which the radio luminosity function is fixed at its $z \simeq 2$ form for all higher redshifts. **Lower Panel:** The high-redshift cumulative redshift distribution of the LBDS ($S_{1.4GHz} > 1$ mJy) sample, compared with the PLE, LDE and no-cutoff model predictions assuming $\alpha_{1.4GHz}^{2.7GHz} \simeq 0.8$.

quasars have confirmed that a very similar, perhaps also luminosity-dependent redshift cutoff is displayed by the quasar RLF (Dunlop & Peacock 1990; Shaver *et al.* 1996). Futhermore, it is now clear that the population of optically-selected QSOs declines at high redshift with, arguably, a comparable luminosity dependence (Warren, Hewett & Osmer 1994; Kennefick *et al.* 1995). The implication is that the similarity between the evolving flat-spectrum RLF, steep-spectrum RLF and QSO OLF seen at $z < 2$ extends right out $z \simeq 4$, and that all powerful AGN suffer a similar form of decline at $z > 2.5$.

However, as is often the case in luminosity function studies, focussing on uncertainty in the precise form of the evolving luminosity function can cloud the fact that evolving *luminosity density* is rather robustly determined. In Fig. 3 I plot the evolving luminosity-weighted integral of the PLE and LDE RLFs. Both models yield essentially the same evolving luminosity density of radio emission out to $z \simeq 5$. In Fig. 3 the evolving luminosity density of radio emission is presented in terms of an evolving black hole fueling rate per Mpc^3 (left-hand axis; see figure caption for details) to enable ease of comparison with the evolving star-formation rate per Mpc^3 deduced by Madau (1997) (data points and right-hand axis in Fig. 3). The similarity between the radio-based curves, and the ultraviolet-based data points in Fig. 3 appears too good to be a coincidence; the agreement is essentially perfect out to $z \simeq 1$ where the star-formation rate is well determined, and at $z > 1$ the curves are undoubtedly consistent with the limits derived from the number density of Lyman-limit galaxies. Indeed, given the superior completeness of the radio surveys one might go so far as to suggest that the curves shown in Fig. 3 provide the current 'best bet' as to the true star-formation density between $z \simeq 1$ and $z \simeq 5$. To bring the data-points at $z \simeq 3$ and $z \simeq 4$ into good agreement with the radio-based prediction requires that the star-formation rate density as currently derived from the Lyman-limit galaxies is under-estimated by a factor $\simeq 3 - 4$ relative to the star-formation census provided at $z < 1$ by the CFRS. It will be interesting to see whether this transpires to be the case, or whether star-formation activity really does peak at redshifts closer to $z \simeq 1$.

At first sight it perhaps seems unlikely that cosmic star-formation activity, which at least at $z < 1$ occurs predominantly in disc/irregular systems, should be traced by the evolution of powerful radio sources which themselves are generally found in old giant elliptical galaxies (even at $z \simeq 1.5$ at least some radio galaxies are > 3 Gyr old; Dunlop *et al.* 1996, Dunlop 1997). However, star-formation rate density presumably reflects the global rate of gravitational accretion/condensation of gas at a given epoch, and it is at least plausible that when such material falls into a massive galaxy containing a black hole, its mass is partly reprocessed as radio emission rather than simply forming a disc of stars. Averaged over a large enough volume, it might not be unreasonable to find that radio luminosity density should reflect the global level of SFR at any given epoch. It remains to be determined whether the stars in the giant elliptical radio-source hosts are themselves formed in the tail of the distribution illustrated in Fig. 3, or whether there exists a separate high-redshift peak of star-formation corresponding to the (perhaps dust-enshrouded) formation epoch of the most massive objects.
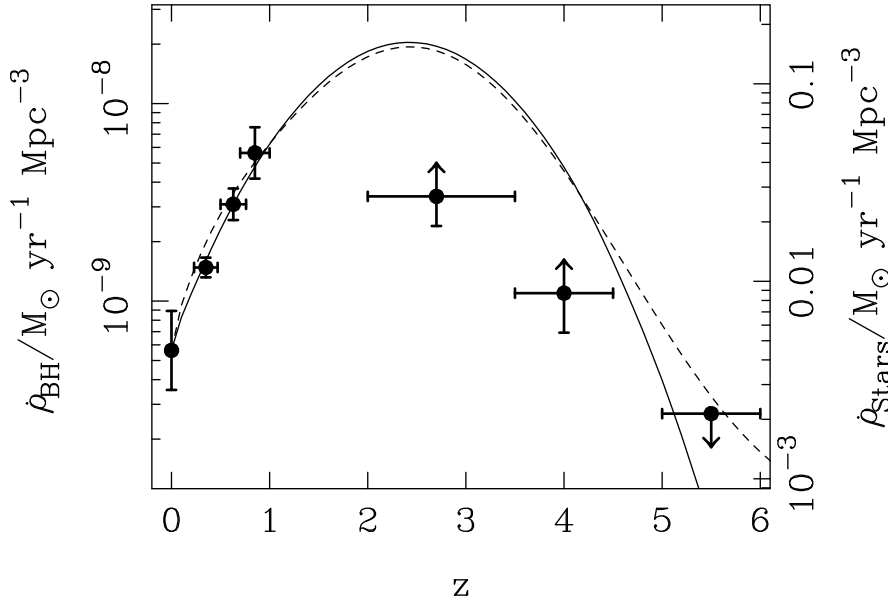
Figure 3. A comparison of the redshift dependence of the rate at which mass is consumed by black holes at the centre of giant elliptical galaxies (and turned into radio luminosity from AGN; curves and left-hand axis) with the rate at which mass is converted into stars per Mpc^3 (and turned into UV-light from primarily disc/irregular galaxies; data points and right-hand axis). The solid and dashed curves are the luminosity-weighted integrals of the PLE and LDE evolving radio luminosity functions shown in Fig. 1, converted into black hole mass consumption rate per Mpc^3 assuming an efficiency of $\simeq 1\%$. The data-points indicating the star-formation history of the Universe are taken from Madau (1997), and are themselves derived from a low-redshift Hα survey ($z \simeq 0$), the Canada France Redshift Survey ($z < 1$), and the number of colour-selected 'U-dropout', 'B-dropout' and (lack of) 'V-dropout' galaxies in the Hubble Deep Field. The upward pointing arrows indicate the fact that the assessment of star-formation rates based on Lyman-limit galaxies is liable to be under-estimated due to the effects of dust.

References

Boyle, B.J., *et al.*, 1993, *MNRAS,* **260**, 49.

Dunlop, J.S., 1994, In: *Frontiers of Space and Ground-based Astronomy: The Astrophysics of the 21st Century*, ESLAB Symp. 27, p.395, eds. Wamsteker, et al., Kluwer.

Dunlop, J.S., 1996, In: *High Sensitivity Radio Astronomy*, p.167, eds. Jackson & Davis, CUP.

Dunlop, J.S., 1997, In: *HST and the High Redshift Universe*, 37th Herstmonceux Conference, eds. Tanvir et al., World Scientific, in press.

Dunlop, J.S. & Peacock, J.A., 1990, *MNRAS,* **247**, 19.

Dunlop, J.S., Peacock, J.A. & Windhorst, R.A., 1995, In: *Galaxies in the Young Universe*, p.84, eds. Hippelein et al., Springer-Verlag.

Dunlop, J.S., *et al.*, 1996, *Nature,* **381**, 581.

Eales, S.A. & Rawlings, S., 1996, *ApJ,* **460**, 68.

Eales, S.A., *et al.*, 1993, *ApJ,* **409**, 578.

Hewett, P.C., Foltz, C.B. & Chaffee, F.H., 1993, *ApJ,* **406**, L43.

Shaver, P.A., *et al.*, 1996, *Nature,* **384**, 439.

Kennefick, J.D., Djorgovski, S.G. & de Carvalo, R.R., 1995, *AJ*, **110**, 2553.

Kron, R.G., Koo, D.C. & Windhorst, R.A., 1985, *A&A,* **146**, 38.

Lilly, S.J., *et al.*, 1995, *ApJ,* **455**, 108.

Madau, P., 1997, In: *Star Formation Near and Far*, Maryland, October 1996, in press.

Madau, P., *et al.*, 1996, *MNRAS,* **283**, 1388.

Rawlings, S., *et al.*, 1996, *Nature,* **383**, 502.

Rowan-Robinson, M., *et al.*, 1993, *MNRAS,* **263**, 123.

Warren, S.J., Hewett, P.C. & Osmer, P.S., 1994, *ApJ,* **421**, 412.

Windhorst, R.A., van Heerde, G.M. & Katgert, P., 1984a, *A&AS,* **58**, 1.

Windhorst, R.A., Kron, R.G. & Koo, D.C., 1984b, *A&AS,* **58**, 39.